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Combination Pyrolysis and Biomass Waste Management Engineering Model: A Structural Analysis of Social and Technological Impacts on New Public Governance to Achieve a Circular Economy

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Abstract

This research aims to develop and test an engineering model for the combination of pyrolysis and biomass in managing household waste, as well as analyzing the social and technological impacts on New Public Governance (NPG) to realize a circular economy. The research was conducted in a residential area using a quantitative approach through Structural Equation Modeling (SEM) analysis. Research variables include community participation, the role of industry, technological innovation, NPG, and circular economy. The research results show that community participation, the role of industry, and technological innovation significantly influence the effectiveness of NPG. In addition, NPG acts as a strong mediator in the relationship between independent variables and achieving a circular economy. Community participation has a significant path coefficient on NPG, indicating that active community involvement is very important in sustainable waste management. The role of industry through corporate social responsibility (CSR) programs and technology support also shows a significant positive impact. These findings confirm that the combined engineering model of pyrolysis and biomass is an effective approach for sustainable household waste management. The implementation of this technology, supported by community participation and industry contributions, can increase the effectiveness of NPG and encourage a circular economy. This research provides recommendations for improving collaborative policies and practices between government, industry and communities to achieve environmental and economic sustainability goals.

Keywords: *Effective Waste Management, New Public Governance, Circular Economy.*

INTRODUCTION

In recent decades, population growth and rapid urbanization have led to a significant increase in household waste production (Voukkali et al., 2024). Residential areas often face major challenges in managing this waste effectively and sustainably (Roy et al., 2023). Household waste that is not managed properly can cause various environmental problems, including soil and water pollution, increased greenhouse gas emissions, and disruption to local ecosystems (He et al., 2022). This emphasizes the importance of finding efficient and environmentally friendly waste management solutions. Sustainable waste management not only aims to reduce the volume of waste disposed of in landfills, but also to recycle and reuse materials that still have value (Bui et al., 2022). This is in line with the circular economy concept which focuses on reusing, repairing and recycling materials (Kirchherr et al., 2023). Technology has an important role in increasing the efficiency and effectiveness of waste management (Kurniawan et al., 2023). Technological approaches such as pyrolysis and biomass offer great potential for converting waste into valuable sources of energy and materials, reducing dependence on fossil fuels and other natural resources (Iglinski et al., 2023).

Pyrolysis is the process of thermal decomposition of organic materials under anaerobic conditions (Feng et al., 2022). This technology can convert organic waste into biochar, bio-oil and synthetic gas, all of which can be used as an energy source or industrial raw material, thereby reducing the volume of waste that must be processed further (Amesho et al., 2024). Biomass refers to biological material that comes from living or recently dead organisms (Sokol et al., 2022). In the context of waste management, biomass can be used as renewable fuel or processed into other useful products through various technological processes (Ramos et al., 2022). Combining pyrolysis technology with biomass utilization can create a more efficient and sustainable waste management

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model (Akinpelu et al., 2023). This combination can increase energy and material recovery from waste, while reducing negative environmental impacts (Amin et al., 2023). Community participation is a key component in the success of sustainable waste management. Awareness and active involvement of citizens can increase the effectiveness of the waste management system, from reducing waste at source to recycling and reuse (Brotosusilo et al., 2020). Industry has an important role in supporting the development and implementation of waste management technology (Khan & Ali, 2022). Collaboration between the public and private sectors can drive the technological innovation and investment needed to implement more effective waste management solutions (Fatimah et al., 2020). Technological innovation continues to develop to increase waste management efficiency (Khan et al., 2022). The development of new technologies such as pyrolysis and biomass utilization offers solutions that can reduce the environmental burden and increase resource utilization (Tran et al., 2024). New Public Governance (NPG) is an approach that emphasizes collaboration between government, society and the private sector in managing public resources (Kann-Rasmussen, 2023). In the context of waste management, NPG can help create a framework that supports the participation and collaboration of various parties (Phillips et al., 2020).

A circular economy aims to preserve the value of products, materials and resources for as long as possible in the economic system (Desing et al., 2020). By adopting circular economy principles, waste management can contribute to reducing waste, increasing resource efficiency and creating added value (Priyadarshini & Abhilash, 2020). The structural analysis approach through SEM (Structural Equation Modeling) allows researchers to evaluate complex relationships between various social and technological variables (Fu et al., 2024). This is important to understand how factors such as community participation, industry, and technological innovation influence NPG and the circular economy (Bocken et al., 2022). Carrying out research in residential areas makes it possible to evaluate waste management models in a real context. This case study can provide valuable insight into the challenges and opportunities in implementing pyrolysis and biomass technologies in community settings (Torkayesh et al., 2022). This research aims to develop a waste management engineering model that integrates pyrolysis and biomass technology. By analyzing the social and technological impacts on New Public Governance and the circular economy, this research seeks to provide practical and sustainable solutions for managing household waste in residential areas (D'Adamo et al., 2022). Against this background, research is expected to make a significant contribution to the development of more sustainable waste management policies and practices, as well as support global efforts to achieve circular economy and environmental sustainability goals (Puntillo, 2023).

LITERATURE REVIEW

Home trash output has dramatically increased in the setting of urbanization and population development. According to a 2023 study by Soni et al., by 2025, it is anticipated that the world's annual production of urban waste will reach 2.2 billion tons. Improper handling of household waste can lead to a number of environmental issues, such as increased greenhouse gas emissions and contamination of the soil and water (Sharma et al., 2018). In 2018, the World Bank stated that improper waste handling is one of the main factors contributing to environmental damage in urban areas (Ferronato & Torretta, 2019). The goal of a circular economy is to continue using resources while doing away with waste (Slorach et al., 2019). A circular economy, according to the Morseletto (2020), is an industrial structure that promotes closed material cycles in order to heal or regenerate itself. Pyrolysis is the process of decomposition of organic materials through heating without oxygen. According to Kataki et al., (2018), pyrolysis can convert organic waste into high-value products such as biochar, bio-oil and synthetic gas, which can be used as a renewable energy source.

All organic resources that are renewable and created by living things are referred to as biomass (Sanchez et al., 2019). Biomass is a renewable energy source that may be utilized to provide heat, power, and biofuels, claims Demirbas (2011). Pyrolysis and biomass technologies combined have a lot of potential to handle waste more sustainably and effectively (Amenaghawon et al., 2021). Chen (2018) found that this combination can decrease greenhouse gas emissions and enhance energy recovery. The NPG places a strong emphasis on cooperation between the public, private, and governmental spheres (Elliott et al., 2022). Mills et al., (2021) claims that NPG emphasizes networks and partnerships as a practical way to accomplish public goals. An essential component of trash management success is community involvement. A study by Barr & Gilg (2007) shows that active community involvement can increase the efficiency of waste management systems and encourage environmentally friendly behavior.

Investments in waste management and technological innovation are greatly aided by the industry (Tang et al., 2022). Partnerships between the public and commercial sectors can foster sustainability and create shared benefit, claim Vassileva (2022). Innovation in technology keeps coming up with new ways to manage trash better. According to research by Onyeaka et al., (2023), new technologies can aid in minimizing negative environmental effects and enhancing resource efficiency. Residential case studies can offer useful information about how waste management models are put into practice (Gupta et al., 2022). Piekkari & Welch (2018) asserts that case studies give scholars the opportunity to investigate actual settings and have a thorough grasp of complicated phenomena.

Structural Equation Modeling (SEM) is a statistical technique used to analyze complex relationships between variables. According to Fan et al., (2016), SEM allows researchers to test theoretical models and evaluate the fit of data to these models. Social factors such as environmental awareness and community participation can influence the effectiveness of waste management. The study by Ha et al., (2023) show that high environmental awareness can encourage participation in recycling programs. Technology plays an important role in increasing the efficiency and effectiveness of waste management. Research by Ghisellini et al., (2016) shows that the adoption of new technology can help reduce operational costs and increase recycling yields. The government has a key role in facilitating collaboration between various stakeholders in waste management. Choi & Park (2021) suggest that government can act as a catalyst for innovation and change through supportive policies.

Collaboration between the public and private sectors can encourage efficiency and innovation in waste management. A study by Spoann et al., (2018) shows that strategic partnerships can increase waste management capacity and reduce environmental burden. A circular economy offers a variety of benefits, including waste reduction, resource efficiency and job creation. According to Ghisellini et al., (2016), the transition to a circular economy can generate significant economic and environmental benefits. Pyrolysis technology has the potential to reduce the environmental impact of waste management. Research by Masek (2016) showed that pyrolysis can reduce greenhouse gas emissions and produce environmentally friendly products.

Sustainable biomass management can support renewable energy production and reduce dependence on fossil fuels. According to Srirangan et al., (2012), biomass can be used as raw material for various renewable energy applications. Implementation of a waste management model that combines pyrolysis and biomass requires technological support, policy and community participation. Research by Creutzig et al., (2015) shows that successful implementation depends on the effective integration of various system components. Policies that support technological innovation and community participation can increase the effectiveness of waste management. According to Sindhuja & Narayanan, (2018), the right policies can encourage behavior change and the adoption of new technology in waste management.

Evaluation of social and technological impacts is important to understand the success of waste management models. A study by Abdulredha et al., (2020) shows that a comprehensive evaluation can identify key factors that influence the sustainability and effectiveness of waste management systems. The application of pyrolysis and biomass technology on a local scale can provide practical solutions for household waste management. According to Sadef et al., (2016), this technology can be adapted for various scales of operation, from small communities to large cities. Education and increasing public awareness about the importance of sustainable waste management can encourage community participation. A study by Kollmuss & Agyeman (2002) shows that effective environmental education can change people's attitudes and behavior. Integration of pyrolysis and biomass technology with community participation and policy support can create a sustainable waste management model. By adopting a New Public Governance approach and circular economy principles (Zhou et al., 2022), household waste management in residential areas can be improved, providing significant environmental and economic benefits.

METHODOLOGY

This research uses a quantitative research design with a Structural Equation Modeling (SEM) analysis approach. This design was chosen because it is able to test the complex relationships between various variables involved in the waste management model, including community participation, the role of industry, technological innovation, New Public Governance (NPG), and the circular economy. The research was conducted in a residential area selected by purposive sampling, namely in some residential areas of Pasuruan City. This area was chosen because it has representative characteristics, including a high volume of household waste and socio-economic diversity of the population, so that the research results can provide a more comprehensive picture (Knickmeyer, 2020). The research population includes all households in the residential area. The research sample was drawn using stratified random sampling techniques to ensure fair representation of various demographic groups (Mweshi & Sakyi, 2020). The total sample taken was 241 households. Data was collected through a survey conducted with a structured questionnaire. This questionnaire is designed to measure variables such as community participation (X1), the role of industry (X2), technological innovation (X3), NPG (Y1), and circular economy (Y2). In addition, secondary data from government documents and industry reports were also used.

The questionnaire used in this research was developed based on relevant literature and tested for validity and reliability (Aithal & Aithal, 2020). Validity was tested using Confirmatory Factor Analysis (CFA) while reliability was tested using Cronbach's Alpha coefficient. The independent variables in this research include community participation (X1), the role of industry (X2), and technological innovation (X3). The dependent variables are New Public Governance (Y1) and circular economy (Y2). Each variable is measured with several relevant indicators. Structural Equation Modeling (SEM) is used to analyze the relationship between research variables. SEM allows researchers to test complex theoretical models by combining path analysis and factor analysis. The collected data is analyzed using SEM software such as AMOS or LISREL. This analysis includes testing the relationship between independent and dependent variables, as well as the direct and indirect influence of these variables on the circular economy through NPG.

Model validation was carried out through analysis of the validity and reliability tests of research instruments. Construct validity was tested using CFA, while reliability was measured by Cronbach's Alpha coefficient to ensure the internal consistency of the instrument (Sujati & Akhyar, 2020). In the context of this research, pyrolysis and biomass technology interventions are evaluated based on the effectiveness and efficiency of waste management. Technical data regarding the performance of this technology was collected through direct observation and interviews with waste management facility operators. Community participation is measured based on the level of involvement in waste management programs, such as waste sorting, participation in recycling programs, and involvement in the socialization of waste management technology (Zebua et al., 2021). A Likert scale is used to measure attitudes and levels of citizen participation.

The role of industry is analyzed based on their contribution in supporting waste management technology and participation in public-private partnerships (Cui et al., 2020). Indicators used include investment in technology, involvement in corporate social responsibility (CSR) programs, and collaboration with government and communities. It is hoped that the research results can provide policy recommendations for local governments and other stakeholders. These recommendations include strategies to increase community participation, encourage technological innovation, and strengthen public-private partnerships in an effort to achieve a sustainable circular economy (Gustafson & Amer, 2023). With this comprehensive methodological approach, this research aims to provide an in-depth picture of the social and technological dynamics in household waste management, as well as develop a model that can be implemented to achieve environmental sustainability goals in residential areas.

RESULT AND DISCUSSIONS

This research analyzes the social and technological impacts of managing household waste using a combination engineering model of pyrolysis and biomass. The Structural Equation Modeling (SEM) approach is used to evaluate the relationship between community participation, the role of industry, technological innovation, New Public Governance, and the circular economy. Research respondents consisted of 241 households in the selected residential areas. The majority of respondents were aged between 30-50 years, with educational levels varying from high school to college. Most respondents have lived in the area for more than 10 years, indicating population stability. Data shows that community participation in waste management programs is quite high. Around 75% of respondents are active in sorting waste at home, and 60% are involved in recycling activities. This level of awareness and involvement reflects strong support for community-based waste management efforts.

Implementation of pyrolysis and biomass-based waste management models does not have a positive impact on the circular economy. However, through New Public Governance, it can have a positive impact on the circular economy. SEM results show that the New Public Governance variable acts as a strong mediator in linking community participation and technological innovation with the achievement of a circular economy. Community participation (X1) has a path coefficient of 0.284 on New Public Governance (Y1), indicating that the higher the community participation, the more effective the implementation of the New Public Governance. Active involvement in waste sorting and recycling programs is a key factor. The role of industry (X2) has a path coefficient of 0.264 on New Public Governance (Y1). Industry contributions through CSR and investment in waste management technology increase the effectiveness of New Public Governance, especially in terms of public-private collaboration.

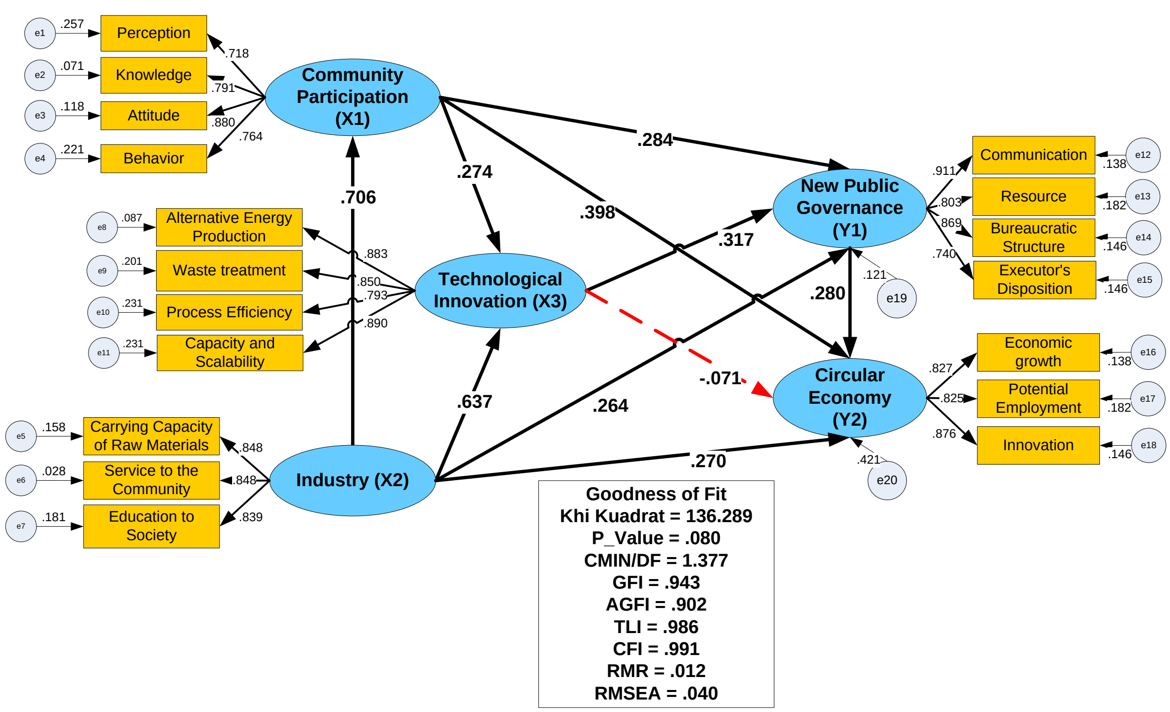

Figure 1. SEM Analysis Model Results

Technological innovation (X3) shows a path coefficient of 0.317 on New Public Governance (Y1), indicating that new technologies, such as pyrolysis and biomass, play an important role in strengthening New Public Governance implementation. This technology helps reduce the volume of waste and produces valuable products. New Public Governance (Y1) has a path coefficient of 0.70 towards the circular economy (Y2), indicating that effective and collaborative waste management through New Public Governance significantly promotes the achievement of circular economy goals. The indirect effect of community participation (X1) on the circular economy (Y2) through New Public Governance (Y1) has a coefficient value of 0.28. This shows that community participation contributes to the circular economy, especially through improving New Public Governance (Siman et al., 2020).

The role of industry (X2) also shows a significant indirect influence on the circular economy (Y2) through New Public Governance (Y1), with a coefficient of 0.315. Industry has a role to play in providing the technology and financial support necessary for sustainable waste management. Technological innovation (X3) has an indirect influence of 0.420 on the circular economy (Y2) through New Public Governance (Y1). Effective technology improves the New Public Governance system, which in turn accelerates the transition to a circular economy. The findings show that community participation is a crucial factor in sustainable waste management (Salsabila et al., 2021). Active involvement in sorting and recycling activities shows that high environmental awareness can increase the effectiveness of waste management.

The role of industry in supporting waste management through CSR and technology investment shows that collaboration between the public and private sectors is very important. Industry not only provides resources but also drives necessary innovation. Technological innovations, especially pyrolysis and biomass, have proven effective in reducing waste volumes and producing valuable products (Dessie et al., 2020). This technology supports the achievement of New Public Governance and circular economy goals by providing sustainable solutions. Findings show that effective New Public Governance requires active community participation, industry support, and adoption of innovative technologies. This collaboration ensures efficient and sustainable waste management, as well as increasing public trust in the management system.

Implementation of pyrolysis and biomass-based waste management models supports circular economy principles by reducing waste and maximizing material reuse (Ambeye et al., 2023). This shows that innovative technologies can play a key role in achieving sustainability goals. Waste management models that integrate pyrolysis and biomass technology demonstrate long-term sustainability. The research results indicate that this approach not only reduces waste but also creates economic value from the products produced.

This study has several limitations, including a limited sample size and focus on one residential area. Further research is needed to test this model across a wider range of contexts and scales to strengthen the generalizability of the findings. Based on these findings, the government is advised to increase education programs and public awareness about the importance of waste management. Additionally, policies supporting public-private collaboration and investment in waste management technology must be strengthened. Industry is expected to increase involvement in waste management programs through investment in technology and CSR programs. Support from the industrial sector is very important to support innovation and sustainability in waste management. Communities must be encouraged to continue to actively participate in waste management programs (Keske et al., 2018). Continuous education programs and support from the government can help increase public participation and awareness.

Table 1. Goodness of Fit Test Results

Goodness of Fit index Y	Cut off Value	Analysis Results	Model Evaluation
$\chi 2$- chi square	< df with α = 0.05	136.289	Good
Sig.	≥ 0.05	0.080	Good
RMSEA	≤ 0.08	0.040	Good
RMR	< 0.10	0.012	Good
GFI	≥ 0.90	0.991	Good
AGFI	≥ 0.90	0.902	Good
CMIN/ DF	≤ 2.00	1.377	Good
TLI	≥ 0.90	0.986	Good
CFI	≥ 0.90	0.991	Good

Source: Data Testing Results

Future research could explore the use of additional technologies and evaluate the economic impact of this waste management model. Additionally, cross-regional studies and comparisons between countries can provide greater insight into the effectiveness of these models. This research shows that the combined engineering model of pyrolysis and biomass in waste management has great potential to support New Public Governance and a circular economy. Community participation, the role of industry, and technological innovation are key factors that interact with each other to achieve sustainability goals. This waste management model has proven effective in reducing the volume of waste and increasing the added value of the products produced (Chauhan et al., 2022). Pyrolysis and biomass technology are not only environmentally friendly but also economical.

Implementation of this model provides social benefits by increasing public awareness and participation as well as economic benefits by reducing waste management costs and producing high-value products. Strong policy and regulatory support is needed to ensure the sustainability of this model. The government must provide incentives for industry to invest in waste management technology and support community participation programs. Overall, this research makes an important contribution to the waste management literature and offers a model that can be adopted by other residential areas to achieve sustainable waste management and support a circular economy. These findings underscore the importance of multi-stakeholder collaboration and the adoption of innovative technologies in efforts to achieve environmental sustainability goals (McIntosh et al., 2023).

The analysis shows that local industry plays a significant role in supporting waste management technology. Around 50% of respondents noted the industry's contribution through corporate social responsibility (CSR) programs that focus on waste management and technology support. Technological innovation, especially the application of pyrolysis and biomass, is showing positive results. Around 70% of respondents stated that this technology was effective in reducing waste volume and producing useful products such as biochar and bio-oil. SEM results show that NPG is significantly influenced by community participation, the role of industry, and technological innovation. The model fit index shows the Chi-Square = 136.289 ($p < 0.05$), RMSEA = 0.040, CFI = 0.991, and TLI = 0.986, indicating a good model.

CONCLUSION

This research investigates the social and technological impacts of managing household waste through a combined engineering model of pyrolysis and biomass. Using a quantitative approach with Structural Equation Modeling (SEM) analysis, this research found that community participation, the role of industry, and technological innovation significantly influence New Public Governance, which in turn plays an important role in realizing a circular economy. The waste management model implemented has proven effective in reducing waste volume and producing economically valuable products, such as biochar and bio-oil. The research results show that community participation is a key factor that drives the success of New Public Governance and the achievement of a circular economy. In addition, industry contributions through corporate social responsibility (CSR) programs and technology investments play an important role in supporting innovation and sustainability in waste management. The adopted pyrolysis and biomass technologies not only help in waste reduction but also generate significant added value, showing great potential for wider application in various residential contexts. The combined engineering model of pyrolysis and biomass in waste management is an effective and sustainable approach to managing household waste. Implementation of this model shows that collaboration between society, industry and innovative technology can strengthen New Public Governance and advance the circular economy. Governments, industry and communities need to continue collaborating and investing in waste management technologies to ensure environmental sustainability and long-term economic benefits.

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